Advanced Perpendicular Magnetic Tunnel Junctions for Computation in Random Access Memory

Daniel B. Gopman
Materials Science & Engineering Division
National Institute of Standards and Technology
Gaithersburg, MD 20899, USA
daniel.gopman@nist.gov

William Taylor
GLOBALFOUNDRIES
Malta, NY 12020, USA

Weigang Wang
Department of Physics
University of Arizona
Tucson, AZ 85721, USA

Tony Low and Jian-Ping Wang
Department of Electrical & Computer Engineering
University of Minnesota
Minneapolis, MN, USA

***Abstract*— Magnetic random access memory (MRAM) based on perpendicular magnetic tunnel junctions (pMTJs) is one of the core building blocks for beyond-Complementary Metal-Oxide Semiconductor (beyond-CMOS) technologies. Their inherent non-volatility, rad-hardness and endurance (10^{16}) makes pMTJs extremely competitive for computation-in-memory and other DoD applications where security and ruggedness are of the utmost vitality. To deliver on the potential of MRAM for computation-in-memory, reductions in the energy- and delay characteristics of pMTJs must be demonstrated. Based on interfacial- and bulk perpendicular magnetic anisotropy materials, we demonstrate two novel perpendicular synthetic antiferromagnet designs for ultra-fast and ultra-low power switching performance. Our stacks are compatible with or close to the existing pMTJ stack and fabrication process, which will make the technology transition to back-end-of-line semiconductor process practical within a 5-10 year time frame.**

Keywords—MRAM; Computational RAM, beyond-CMOS; spintronics; rad-hard

I. INTRODUCTION (*HEADING 1*)

The Magnetic Tunnel Junction (MTJ) is one of the core building blocks for beyond-CMOS technologies. Compared to other beyond-CMOS device platforms, MTJs offer several unique advantages, including low-voltage write; simple lithographic compatibility (only three masks) directly onto CMOS electrodes; and nearly a generation of invested research and development due to the success of the MTJ as read-head sensor in magnetic hard disk drives. Two particularly unique factors stand out for their ability to enable computation-in-memory and other DoD applications. The first factor is the inherent non-volatility of the data storage layers, yielding essential radiation hardness, instant power-on, non-destructive data read-out, and security in hardware. And the second factor is endurance up to 10^{16} read/write cycles and above, which is three orders of magnitude better than any reported memory cells. This provides necessary robustness for a true computation-in-memory and computation-near-memory arrays.

Advancement of MTJs in the past decade has led to successful magnetic random-access memory (MRAM) products, including toggle-MRAM (Everspin, IBM, Honeywell) and STT-MRAM (Everspin, GLOBALFOUNDRIES, IBM, Intel, Samsung, TSMC, Avalanche Technology). Future commercialization opportunities are envisioned where the MTJ device is implemented as a building block for true computation in random access memory (CRAM) because of its superior endurance performance that is needed for computation [1-3]. State of the art performance metrics for the best performing perpendicularly magnetized MTJs (pMTJs) have been demonstrated recently: ultrahigh tunnel magnetoresisntance (TMR) (208%) in p-MTJs with interfacial perpendicular magnetic anisotropy (PMA) and ultralow write delays (t_{SW} ~ 165 ps at 50% switching probability) [4-5]. To enable true CRAM, as shown in Fig. 1, industry needs higher TMR ratio (>500%) MTJs and much lower write delay (<50 ps) with reasonably low

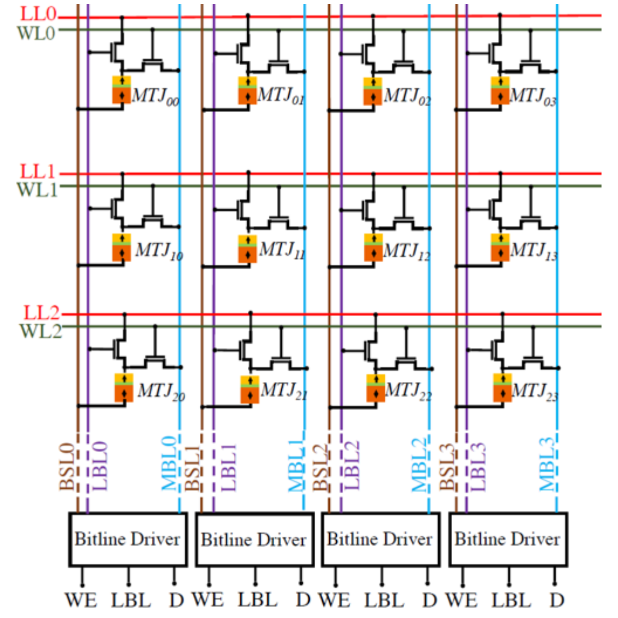


FIGURE 1: MRAM-based CRAM. LL, WL, BSL, LBL and MLM = Logic Line, Word Line, Bit Select Line, Logic Bit Line and Memory Bit Line

---

operation energy (E_{SW} ~50 aJ per write operation, read is already negligibly low) and high thermal stability (Δ = 60 k_BT). These numbers are from the preliminary benchmarking effort for CRAM. In theory, the highest TMR for a MgO-barrier based MTJ could reach 35,000% with right materials and interfaces, and the write delay could be reduced to below 10 ps with optimized materials and switching mechanisms [6]. Our approach seeks to advance MTJs toward these performance specifications so that the CRAM topology, among several emerging MTJ-based computing topologies, and future high-density MRAM products can become a reality.

An MTJ with engineered perpendicular magnetic anisotropy (PMA) relative to the planes of the layered heterostructure, or pMTJ, is an essential building block for advanced MTJs. The PMA materials are promising candidates for the development of ultra-high-density spintronic memory and logic devices due to their high thermal stability, scalability, and ultra-low power consumption. Interfacial PMA materials such as the Ta/CoFeB/MgO stack possess a PMA (K_u) of ~(0.2-0.5) MJ/m^3 and an α of ~0.015-0.027 [7-9]. Considerable progress has been made in the application of interfacial PMA materials to STT-MRAM [10-12]. Bulk PMA materials such as L1$_0$-FePd [13-17] and Mn-based perpendicular Heusler alloys [18-21] have an even larger K_u (1.3 MJ/m^3-1.4 MJ/m^3), a lower α (0.002~0.015), and a low processing temperature (200 °C - 400 °C). These properties make them ideal for ultra-high density and ultra-low power consumption memory devices. Furthermore, the write current density (J_c) for perpendicular spintronic devices is defined by the equation $J_c = 2\alpha e t_F M_s \left(H_{appl} + H_k\right)/\hbar\eta$ [22], where J_c mainly relates to the α, the saturation magnetization (M_S), and the K_u. Notably, switching time is proportional to M_S. However, for interfacial PMAs (such as the Ta/CoFeB/MgO stack) and bulk PMA L1$_0$-FePd thin films, their M_S=(1100~1300) kA/m, which is relatively high.

Synthetic antiferromagnetic (SAF) structures, comprised of two ferromagnetic layers aligned in an antiparallel arrangement and separated by a thin (<1 nm) metallic spacer, are used extensively in multilayered magnetic sensors and memories [23], which is one of promising methods to obtain the fast switching time by reducing the M_s of the ferromagnetic layer in pMTJs [24-26]. Owing to the nearly net-zero flux configuration, SAFs are generally implemented as the reference layer to compensate the deleterious offset fields from other layers. More recently, SAFs were demonstrated to show the potential for faster write operation in magnetic domain-wall memories compared with single-layer counterparts due to additional torques on the magnetization induced by the interlayer coupling field [27]. A recent simulation has made a similar argument for single-domain MRAMs in which a SAF *free layer* replaces the single magnetic layer [28]. This work, supported partially by the DARPA-sponsored STARnet research center C-SPIN, shows that the design of a SAF-MTJ using conventional interfacial PMA materials in construction of a SAF free layer can enable switching energy-delay products on the order of 100 aJ-10 ps for a 10 nm diameter free layer with a 60 k_BT thermal stability factor, where k_B is the Boltzmann constant and T is the ambient temperature (300 K).

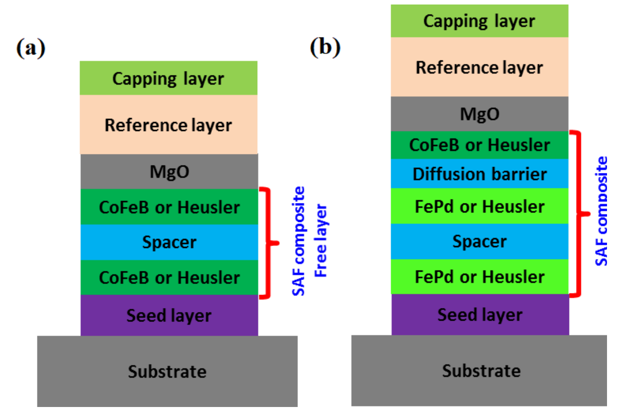


FIGURE 2: (a) The designed interfacial perpendicular SAF(p-SAF) structure, in which the CoFeB and Co-based in-plane Heusler alloys will be used as a ferromagnetic layer and Ru, Ta, Cr will be as a spacer to generate the synthetic-AFM, and Gd will be a spacer to lead to synthetic-ferrimagnetic layer. (b) The designed bulk p-SAF structure with L1$_0$-FePd and Mn-based perpendicular Heusler alloys as a ferromagnetic layer and Ru and Cr as a spacer.

In addition, PI Jian-Ping Wang recently developed a perpendicular interfacial synthetic-ferrimagnetic structure (CoFeB/Gd/CoFeB) and realized field-free switching using spin orbit torques [29], and the bulk L1$_0$-FePd p-SAF composite free layer as well as the integration into p-MTJs and the 25% TMR ratio has been obtained at room temperature after 350 °C post-annealing, even up to ~13% after 400 °C post-annealing [30].

Ultrafast STT switching in the sub-ns regime is one of the key issues for STT-RAM development. One of the crucial limitations for ultrafast switching is the incubation delay induced by pre-switching oscillation [31]. Several approaches have been proposed to minimize pre-switching oscillations in order to improve the switching speed in spin valves such as developing all perpendicular structures [32], applying a hard axis field to set the free layer equilibrium away from the easy axis [33], and adding an extra perpendicular polarizer [34-36]. As of now, limited work has been done on sub-nanosecond STT switching in MTJs. Minimum switching times of 400–580 ps at 50% switching probability have been reported in conventional in-plane MTJs [37]. By adding a perpendicular polarizer, Liu *et al*. showed 100% switching at 500 ps with external field assistance in their MTJ device [38]. Rowlands *et al* achieved 50% switching probability at 120 ps under zero bias field in a fully orthogonal MTJ [39]. For this present approach, a notable achievement is the observation of 165(190) ps at 50(98)% switching probabilities in in-plane magnetized MTJs [5]. However, switching probabilities have not been studied extensively in p-MTJs – with the exception being a single simulation work for a SAF-MTJ using conventional interfacial PMA materials in construction of a SAF free layer can enable switching energy-delay products on the order of 100 aJ-10 ps for a 10 nm diameter free layer. With voltage controlled magnetic anisotropy (VCMA) [40], the switching energy of conventional pMTJs can be further reduced to sub-10 fJ level [41,42]. However, due to the precessional nature of the switching, the time of the pulse voltage has to be accurately controlled, giving rise to a write error rate (WER) of 10^{-5}, which far exceeds the tolerable limits for reliable chip-level performance [43]. We are exploring a unique Even-VCMA effect where voltages with both polarities can reduce the PMA; this is theoretically predicted when the Fermi level of the FM is precisely controlled. With the advanced SAF structure developed in the proposal, STT and Even-VCMA can work together in a complimentary fashion, eventually leading to ultra-low energy (<100 aJ), ultra-low WER (< 10^{-10}) and ultra-fast (< 50 ps) switching.

The key specifications for advanced pMTJs for computational random access memory systems are: ultra-high TMR ratio (>500%); ultra-fast switching (50 ps for 50% switching probability of a 60 k_BT pMTJ); ultra-low switching energy (100 aJ); ultra-small feature size (10 nm) and low damping constant for the magnetic storage layer (<0.01). This provides necessary robustness for a true computation-in-memory and computation-near-memory arrays.

With the realization of advanced pMTJs for computational random access memory (CRAM) systems, significant gains can be realized over classic, near- and edge memory computing. By using memory cells to carry out computation, one gains a 1400-fold improvement over near-memory computing in execution time, and a 40-fold energy reduction [44]. Surprisingly, our team has discovered a realization of a spintronic, reconfigurable in-memory binary neural network accelerator that performs with greater energy efficiency and throughput on image classification and genomics kernel tasks than corresponding CPU-, GPU- and FPGA-based implementations [45].

II. ACHIEVING ULTRAFAST SWITCHING MTJS

To reach ultimate fast switching, a balanced SAF (with near zero net magnetization) is desired. However, such a balanced SAF would require an extremely large exchange coupling constant which is not practical. Therefore, aside from the gains in write speed realized by the SAF structure, additional reduction in write delay may be achieved by electric-field tuning of the PMA using the so-called even voltage control of magnetic anisotropy (even-VCMA) effect.

Indeed, a promising approach to reduce the overall switching energy (E_{SW}) in MTJs is utilizing the interfacial perpendicular magnetic anisotropy (PMA) at the FM/oxide interface and the corresponding VCMA effect [40-42,46-48], where the MTJ can be precessionally switched by an effective in-plane field generated by a sub-ns voltage pulse. We have achieved a low switching current at (10^8-10^9) A/m^2 with fast speed at 400 ps, corresponding to a low E_{SW} that is below 10 fJ. However, due to the precessional nature of switching, the MTJ can be only be switched in a very tight window in VCMA, giving rising to a write error rate much larger than STT (10^{-10}). The core structure is CoFeB (0.9 nm)/MgO (1.6 nm)/CoFeB (1.5 nm), with thicknesses reported in parentheses. However, in another device with a very similar structure, we were able to extend the switching window from 0.5 ns to more than 1 ns with an external field applied in-plane instead of at 40°. This will lead to significantly lower write errors and higher tolerance for device-to-device variability.

The key to reducing switching energy and switching time with interfacial SAF free layer is to utilize the VCMA effect to lower the energy barrier during switching. The efficiency of VCMA is characterized by the change of interfacial magnetic anisotropy density per unit electric field, $\Delta K_S/\Delta E_{ext}$. With the Even-VCMA effect where the STT and VCMA can be combined, truly ultra-low energy and ultra-fast switching is possible, simultaneously with a very low WER that is comparable to STT alone.

III. DEVELOPMENT OF SAF MTJS

A. *Interfacial PMA MTJ*

Consistent with current state-of-the art approaches, we designed p-MTJs with interfacial perpendicular SAF free layers for sub-100 ps switching (see Fig. 2(a)). We have already achieved above 200% TMR with Mo dusting layers inserted at the Ta/CoFeB interface [4]. Unlike thick Mo layers that exhibited a strong (110) crystalline texture, the inserted Mo layer between Ta/CoFeB had little negative influence on the crystallization of CoFe (001), thereby combining the advantages of Mo as a good thermal barrier and Ta as a good boron sink. We envision possible solutions using other heavy metal insertions, to include W and Hf, which have potential to provide higher TMR.

A highlight of the enhanced TMR of a Mo-dusted pMTJ is shown in Fig. 3(a). The barrier thickness for this sample is 3 nm [49]. The black curve at room temperature (RT) exhibits sharp resistance switching with a TMR value of 200%. Then the sample is cooled to low temperature under zero magnetic field. The resistance of the antiparallel state (R_{AP}) consistently increases with decreasing temperature, while the resistance of the parallel state (R_P) remains largely unchanged, leading to a gigantic TMR value approaching 400% [49]. A fascinating phenomena emerges when the sample is cooled under a constant magnetic field of +0.4 T. Unlike the TMR curve measured at RT, where the switching fields of the soft and hard CoFeB layers are symmetric about zero field, the switching fields at 20 K are shifted toward the negative field (black curve). Reversing the cooling field to -4000 Oe changes the switching fields to the positive direction as shown by the red curve in Fig. 3(b). This is direct evidence of an exchange bias effect in the system, which we have determined is an artefact of emergent antiferromagnetism associated with the Fe (Co)-O bonding at the CoFeB/MgO interfaces and could serve as an

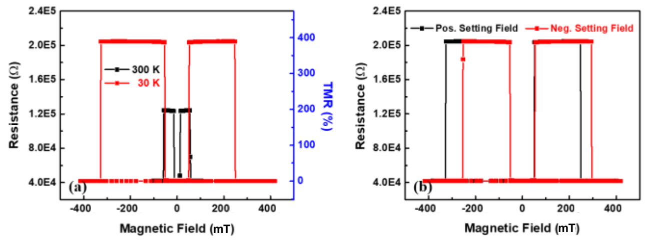


FIGURE 3: (a) Representative TMR curves for pMTJs with Mo insertion layers at RT (Black) and 20 K (Red), a clear exchange bias can be observed at 20 K. (b) Isothermal switching of exchange bias with external field at 20 K.

additional way to enhance the TMR and increase the write speed of pMTJs through control of interfacial oxidation.

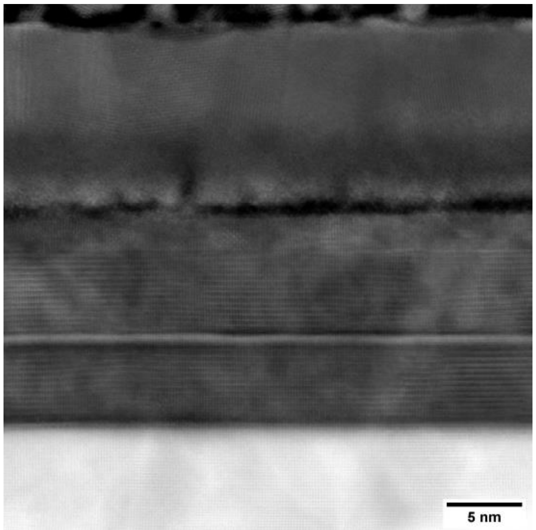


FIGURE 4: Transmission electron micrograph of FePd/Heusler bulk pSAF MTJ showing abrupt interfaces and highly crystalline layers.

The high probability switching of interfacial p-MTJs has been demonstrated in 100 nm diameter nanopillars. Our p-MTJs comprising a Ta/CoFeB/MgO free layer, rapid thermal annealed for 5 minutes at 300 °C exhibit a significant VCMA effect that enables fast, reliable switching at 200 ps. We report switching probability greater than 90% for a 200 ps pulse and 40 fJ switching energy. By engineering a thicker MgO tunneling barrier (approximately 50% thicker than the previous sample), the switching energy of a 100 nm p-MTJ can be reduced to 9 fJ, with a modest reduction in switching probability, showing the value of VCMA toward low energy-delay write.

B. Bulk PMA MTJ

The p-SAF structure with bulk PMA FePd thin films has been developed and integrated into p-MTJs as a free layer (see Fig. 2(b)). The p-SAF structure using bulk PMA FePd thin films through an fcc phase Ru spacer were designed and developed [30]. We additionally demonstrated the p-SAF structure through an fcc phase Ir spacer coupled directly to a spin-polarizing Heusler alloy layer. A full pMTJ based on this structure exhibits cube-on-cube growth with (001) texture from the Cr/Pt buffer up through the MTJ (see Fig. 4). It can be found that the $L1_0$-phase FePd p-SAF structure presents good PMA and antiferromagnetic coupling properties with a square shape minor M-H loop and a net remanent magnetization ~500 kA/m. The PMA constant K_u of the FePd p-SAF structure was then evaluated to be ~1.05 MJ/m^3 based on its M_s and H_K from the *M-H* loops, which is several times larger than that of interfacial PMA materials. The J_{iec} of the FePd p-SAF structure was calculated to be ~ -2.86 mJ/m^2, which is about one order of magnitude larger than that of the $[Co/Pd]_n$ p-SAF system with the same post-annealing temperature [50].

IV. BENCHMARKING AND METRICS OF SAF MTJS FOR FAST SWITCHING

The relevant metrics of SAF pMTJs for fast switching and implementation as advanced MTJs for computation in random access memory have informed the development activities described above. These include device size, switching delay, switching energy, write error rate, thermal stability, tunneling magnetoresistance and the damping constant. For the interfacial p-MTJs, these results are specific to the CoFeB/MgO/CoFeB p-MTJ system. Here we have successfully engineered 100 nm nanopillars with energy-delay product 9 fJ-200 ps, and that are thermally stable with TMR exceeding 100%. The switching probability of these devices was 80% and damping constant 0.01.

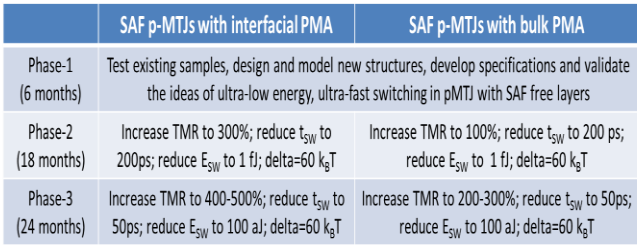
For the bulk SAF pMTJs, strategies have been developed to identify the useful buffer layers that can engineer a large perpendicular magnetic anisotropy in FePd, thereby providing thermal stability down to 10 nm diameter nanopillars. We find that these include Pt, Ru, Ir, Rh, but not Mo or Ta [14]. This is consistent with the need for a fcc (001) buffer whose in-plane lattice parameter is comparable with the in-plane lattice parameter of FePd (0.385 nm). We have also shown the ability to engineer a bulk SAF trilayer using FePd/Ru/FePd, FePd/Ir/FePd and FePd/Rh/FePd. We find that Ru and Ir spacers are more thermally stable over the high-temperature growth and annealing treatment than the Rh spacer and can convey a net zero magnetization state at zero applied field, a prerequisite of a SAF device.

V. CONCLUSIONS

To deliver on the potential of MRAM for computation-in-memory, reductions in the energy- and delay characteristics of pMTJs must be demonstrated. Based on interfacial- and bulk perpendicular magnetic anisotropy materials, we believe there is a path to developing two novel perpendicular synthetic antiferromagnet (p-SAF) designs for ultra-fast and ultra-low power switching performance: one using interfacial PMA materials and one using bulk PMA materials. Our stacks are compatible with or close to the existing p-MTJ stack and fabrication process, which can transition to back-end-of-line semiconductor process practical within a 5-10 year time frame within our near-term roadmap shown in Fig. 5.

ACKNOWLEDGMENT

This work is funded in part by DARPA HR001117S0056—FP—042 "Advanced MTJs for computation in and near random



	SAF p-MTJs with interfacial PMA	SAF p-MTJs with bulk PMA
Phase-1 (6 months)	Test existing samples, design and model new structures, develop specifications and validate the ideas of ultra-low energy, ultra-fast switching in pMTJ with SAF free layers	
Phase-2 (18 months)	Increase TMR to 300%; reduce t_{SW} to 200ps; reduce E_{SW} to 1 fJ; delta=60 k_BT	Increase TMR to 100%; reduce t_{SW} to 200 ps; reduce E_{SW} to 1 fJ; delta=60 k_BT
Phase-3 (24 months)	Increase TMR to 400-500%; reduce t_{SW} to 50ps; reduce E_{SW} to 100 aJ; delta=60 k_BT	Increase TMR to 200-300%; reduce t_{SW} to 50ps; reduce E_{SW} to 100 aJ; delta=60 k_BT

FIGURE 5: Roadmap to demonstration of advanced MTJs for CRAM.

access memory," NSF ECCS, NSF MRSEC and Minnesota Nanofabrication Center (MNC) facility and by NIST [51].

REFERENCES

[1] H. Meng, J. Wang and J. P. Wang "A Spintronics Full Adder for Magnetic CPU", IEEE Electron Dev. Lett., 26, 360 (2005).

[2] A. Lyle, S. Patil, et al, "Direct Communication Between Magnetic Tunnel Junctions for Non-Volatile Logic Fan-Out Architecture," Appl. Phys. Lett. 97, 152504 (2010)

[3] J. P. Wang and J. D. Harms, "General structure for computational random access memory (CRAM)," 2013. US Patent 9,224,447 B2.

[4] H. Almasi, M. Xu, Y. Xu, T. Newhouse-Illige, and W. Wang, "Effect of Mo insertion layers on the magnetoresistance and perpendicular magnetic anisotropy in Ta/CoFeB/MgO junctions." Appl. Phys. Lett., 109(3), 032401 (2016).

[5] H. Zhao, A. Lyle, Y. Zhang, P. K. Amiri, G. Rowlands, Z. Zeng, J. Katine, H. Jiang, K. Galatsis, K. L. Wang, I. N. Krivorotov, and J.-P. Wang, "Low writing energy and sub nanosecond spin torque transfer switching of in-plane magnetic tunnel junction for spin torque transfer random access memory," J. Appl. Phys. 109, 07C720 (2011)

[6] X.-G. Zhang and W. H. Butler, "Large magnetoresistance in bcc Co/MgO/Co and FeCo/MgO/FeCo tunnel junctions," Phys. Rev. B 70, 172407 (2004).

[7] S. Ikeda, K. Miura, H. Yamamoto, K. Mizunuma, H. D. Gan, M. Endo, S. Kanai, J. Hayakawa, F. Matsukura and H. Ohno, "A perpendicular-anisotropy CoFeB-MgO magnetic tunnel junction," Nat. Mater. 9, 721 (2010).

[8] H. Sato, M. Yamanouchi, K. Miura, S. Ikeda, H. D. Gan, K. Mizunuma, R. Koizumi, F. Matsukura, and H. Ohno, "Junction size effect on switching current and thermal stability in CoFeB/MgO perpendicular magnetic tunnel junctions," Appl. Phys. Lett. 99, 042501 (2011).

[9] S. Iihama, S. Mizukami, H. Naganuma, M. Oogane, Y. Ando, and T. Miyazaki, "Gilbert damping constants of Ta/CoFeB/MgO(Ta) thin films measured by optical detection of precessional magnetization dynamics," Phys. Rev. B 89, 174416 (2014).

[10] P. Khalili Amiri, Z. M. Zeng, J. Langer, H. Zhao, G. Rowlands, Y.-J. Chen, I. N. Krivorotov, J.-P. Wang, H. W. Jiang, J. A. Katine, Y. Huai, K. Galatsis, and K. L. Wang, "Switching current reduction using perpendicular anisotropy in CoFeB-MgO magnetic tunnel junctions," Appl. Phys. Lett. 98, 112507 (2011).

[11] H. Sato, E. C. I. Enobio, M. Yamanouchi, S. Ikeda, S. Fukami, S. Kanai, F. Matsukura, and H. Ohno, "Properties of magnetic tunnel junctions with a MgO/CoFeB/Ta/CoFeB/MgO recording structure down to junction diameter of 11 nm," Appl. Phys. Lett. 105, 062403 (2014).

[12] W.-G. Wang, M. Li, S. Hageman, and C. L. Chien, "Electric-field-assisted switching in magnetic tunnel junctions," Nat. Mater. 11, 64 (2012).

[13] D. Weller, A. Moser, L. Folks, M. E. Best, W. Lee, M. F. Toney, M. Schwickert, and J.-U. Thiele, M. F. Doerner, "High Ku Materials Approach to 100 Gbits/in^2," IEEE Trans. Magn. 36, 10 (2000).

[14] X. Wang, S. Krylyuk, D. Josell, D. Zhang, J.-P. Wang and D. B. Gopman, "Buffer layer engineering of L1$_0$ FePd thin films with large perpendicular magnetic anisotropy," AIP Advances 11, 025106 (2021).

[15] D. Zhang, D. Huang, R. Wu, D. Lattery, J. Liu, X. Wang, D. B. Gopman, K. A. Mkhoyan, J.-P. Wang and X. Wang, "Low Gilbert damping and high thermal stability of Ru-seeded L1$_0$-phase FePd perpendicular magnetic thin films at elevated temperatures," Appl. Phys. Lett. 117, 082405 (2020).

[16] H. Naganuma, G. Kim, Y. Kawada, N. Inami, K. Hatakeyama, S. Iihama, K. M. N. Islam, M. Oogane, S. Mizukami, and Y. Ando, "Electrical detection of millimeter-waves by magnetic tunnel junctions using perpendicular magnetized L1$_0$-FePd free layer," Nano Lett. 15, 623 (2015).

[17] S. Iihama, M. Khan, H. Naganuma, M. Oogane, T. Miyazaki, S. Mizukami, and Y. Ando, "Magnetization Dynamics and Damping for L1$_0$-FePd Thin Films with Perpendicular Magnetic Anisotropy," J. Magn. Soc. Jpn. 39, 57 (2015).

[18] H. Kurt, K. Rode, M. Venkatesan, P. Stamenov, and J. M. D. Coey, "High spin polarization in epitaxial films of ferrimagnetic Mn$_3$Ga," Phys. Rev. B 83, 020405(R) (2011).

[19] S Mizukami, F Wu, A Sakuma, J Walowski, D Watanabe, T Kubota, X Zhang, H Naganuma, M Oogane, Y Ando, T Miyazaki, "Long-lived ultrafast spin precession in manganese alloys films with a large perpendicular magnetic anisotropy," Phys. Rev. Lett. 106, 117201(2011).

[20] S. Mizukami, A. Sugihara, S. Iihama, Y. Sasaki, K. Z. Suzuki, T. Miyazaki, "Laser-induced THz magnetization precession for a tetragonal Heusler-like nearly compensated ferromagnet," Appl. Phys. Lett. 108, 012404 (2016).

[21] T. Kubota, Q. L. Ma, S. Mizukami, X. M. Zhang, H. Naganuma, M. Oogane, Y. Ando and T. Miyazaki, "Magnetic tunnel junctions of perpendicularly magnetized L1$_0$-MnGa/Fe/MgO/CoFe structures: Fe-layer-thickness dependences of magnetoresistance effect and tunnelling conductance spectra," J. Phys. D: Appl. Phys. 46 155001(2013).

[22] Z. Diao, Z. Li, S. Wang, Y. Ding, A.Panchula, E. Chen, L.-C. Wang and Y. Huai, "Spin-transfer torque switching in magnetic tunnel junctions and spin- transfer torque random access memory," J. Phys.: Condens. Matter 19, 165209 (2007).

[23] R. A. L. Duine, K.-J. Lee, S. S. P. Parkin, and M. D. Stiles, "Synthetic Antiferromagnetic Spintronics," Nature Physics 14, 217 (2018).

[24] A. Bergman, B. Skubic, J. Hellsvik, L. Nordström, A. Delin, and O. Eriksson, "Ultrafast switching in a synthetic antiferromagnetic magnetic random-access memory device," Phys. Rev. B 83, 224429 (2011).

[25] C. Y. You, "Effect of the synthetic antiferromagnetic polarizer layer rigidness on the spin transfer torque switching current density," Appl. Phys. Lett. 103, 042402 (2013).

[26] X. G. Xu, D. L. Zhang, X. Q. Li, J. Bao, Y. Jiang, and M. B. A. Jalil, "Synthetic antiferromagnet with Heusler alloy ferromagnetic layers," J. Appl. Phys. 106, 123902 (2009).

[27] S. H. Yang, K. S. Ryu, and S. Parkin, "Domain-wall velocities of up to 750 m s-1 driven by exchange-coupling torque in synthetic antiferromagnets," Nature Nanotechnology, 10, 221 (2015).

[28] K. Y. Camsari, A. Z. Pervaiz, R. Faria, E. E. Marinero, and S. Datta, "Ultrafast Spin-Transfer-Torque Switching of Synthetic Ferrimagnets," IEEE Magn. Lett. 7, 3107205 (2016).

[29] J.-Y. Chen, Mahendra DC, D. L. Zhang, Z. Zhao, M. Li, and J.-P. Wang, "Field-free spin-orbit torque switching of composite perpendicular CoFeB/Gd/CoFeB layers utilized for three-terminal magnetic tunnel junctions," Appl. Phys. Lett. 111, 012402 (2017).

[30] D. L. Zhang, C. Sun, Y. Lv, K. B. Schliep, Z. Zhao, J.-Y. Chen, P. M. Voyles, and J.-P. Wang, "L1$_0$-FePd Synthetic Antiferromagnet Through a Face-centered-cubic Ruthenium Spacer Utilized for Perpendicular Magnetic Tunnel Junctions," 9, 044028 (2018).

[31] T. Devolder, C. Chappert, J. A. Katine, M. J. Carey, and K. Ito, "Distribution of the magnetization reversal duration in subnanosecond spin-transfer switching," Phys. Rev. B 75, 064402 (2007).

[32] D. Bedau, H. Liu, J.-J. Bouzaglou, A. D. Kent, J. Z. Sun, J. A. Katine, E. E. Fullerton, and S. Mangin, "Ultrafast spin-transfer switching in spin valve nanopillars with perpendicular anisotropy," Appl. Phys. Lett. 96, 022514 (2010).

[33] T. Devolder, P. Crozat, J.-V. Kim, and C. Chappert, K. Ito, J. A. Katine and M. J. Carey, "Magnetization switching by spin torque using subnanosecond current pulses assisted by hard axis magnetic fields," Appl. Phys. Lett. 88, 152502 (2006).

[34] C. Papusoi, B. Delaët, B. Rodmacq, D. Houssameddine, J.-P. Michel, U. Ebels, R. C. Sousa, L. Buda-Prejbeanu, and B. Dieny, "100 ps precessional spin-transfer switching of a planar magnetic random access memory cell with perpendicular spin polarizer," Appl. Phys. Lett. 95, 072506 (2009)

[35] O. J. Lee, V. S. Pribiag, P. M. Braganca, P. G. Gowtham, D. C. Ralph, and R. A. Buhrman, "Ultrafast switching of a nanomagnet by a combined out-of-plane and in-plane polarized spin current pulse," Appl. Phys. Lett. 95, 012506 (2009);

[36] J-M. L. Beaujour, D. B. Bedau, H. Liu, M. R. Rogosky, A. D. Kena, "Spin-transfer in nanopillars with a perpendicularly magnetized spin polarizer," Proc. SPIE 7398 73980D (2009).

[37] T. Aoki, Y. Ando, M. Oogane, and H. Naganuma, "Reproducible trajectory on subnanosecond spin-torque magnetization switching under a zero-bias field for MgO-based ferromagnetic tunnel junctions," Appl. Phys. Lett. 96, 142502 (2010)

[38] H. Liu, D. Bedau, D. Backes, J. A. Katine, J. Langer, and A. D. Kent, "Ultrafast switching in magnetic tunnel junction based orthogonal spin transfer devices," Appl. Phys. Lett. 97, 242510 (2010)

[39] G. E. Rowlands, T. Rahman, J. A. Katine, J. Langer, A. Lyle, H. Zhao, J. G. Alzate, A. A. Kovalev, Y. Tserkovnyak, Z. M. Zeng, H. W. Jiang, K. Galatsis, Y. M. Huai, P. Khalili Amiri, K. L. Wang, I. N. Krivorotov, and J.-P. Wang, "Deep subnanosecond spin torque switching in magnetic tunnel junctions with combined in-plane and perpendicular polarizers," Appl. Phys. Lett. 98, 102509 (2011)

[40] F. Matsukura, Y. Tokura, and H. Ohno, "Control of magnetism by electric fields," Nat. Nanotechnol. 10, 209, (2015).

[41] C. Grezes, F. Ebrahimi, J. G. Alzate, X. Cai, J. A. Katine, J. Langer, B. Ocker, P. Khalili, and K. L. Wang, "Ultra-low switching energy and scaling in electric-field-controlled nanoscale magnetic tunnel junctions with high resistance-area product," Appl. Phys. Lett. 108, 12403 (2016).

[42] S. Kanai, F. Matsukura, and H. Ohno, "Electric-field-induced magnetization switching in CoFeB/MgO magnetic tunnel junctions with high junction resistance," Appl. Phys. Lett. 108, 192406 (2016).

[43] J. J. Nowak, R. P. Robertazzi, J. Z. Sun, G. Hu, J. H. Park, J. Lee, A. J. Annunziata, G. P. Lauer, R. Kothandaraman, E. J. O Sullivan, P. L. Trouilloud, Y. Kim, and D. C. Worledge, "Dependence of Voltage and Size on Write Error Rates in Spin-Transfer Torque Magnetic Random-Access Memory," IEEE Magn. Lett. 7, 4 (2016).

[44] M. Zabihi, Z. Chowdhury, Z. Zhao, U. R. Karpuzcu, J. Wang, S. Sapatnekar, "In-memory processing on the spintronic CRAM: From hardware design to application mapping", IEEE Trans. Comput., 68, 1159 (2018)

[45] Salonik Resch, S. Karen Khatamifard, Zamshed Iqbal Chowdhury, Masoud Zabihi, Zhengyang Zhao, Jian-Ping Wang, Sachin S. Sapatnekar, and Ulya R. Karpuzcu. 2019. PIMBALL: Binary Neural Networks in Spintronic Memory. ACM Trans. Archit. Code Optim. 16, 4, 41 (2019).

[46] W. Skowroński, T. Nozaki, D. D. Lam, Y. Shiota, K. Yakushiji, H. Kubota, A. Fukushima, S. Yuasa, and Y. Suzuki, "Underlayer material influence on electric-field controlled perpendicular magnetic anisotropy in CoFeB/MgO magnetic tunnel junctions," Phys. Rev. B 91, 184410 (2015).

[47] M. Weisheit, S. Fähler, A. Marty, Y. Souche, C. Poinsignon, and D. Givord, "Electric field-induced modification of magnetism in thin-film ferromagnets," Science **315**, 349 (2007).

[48] Y. Shiota, T. Nozaki, F. Bonell, S. Murakami, T. Shinjo, and Y. Suzuki, "Induction of coherent magnetization switching in a few atomic layers of FeCo using voltage pulses," Nat. Mater. **11**, 39 (2012).

[49] M. Xu *et al.*, "Voltage-Controlled Antiferromagnetism in Magnetic Tunnel Junctions," *Phys. Rev. Lett.*, vol. 124, no. 18, p. 187701, 2020, doi: 10.1103/PhysRevLett.124.187701.

[50] J.-B. Lee, G.-G. An, S.-M. Yang, H.-S. Park, W.-S. Chung, and J.-P. Hong, "Thermally robust perpendicular Co/Pd-based synthetic antiferromagnetic coupling enabled by a W capping or buffer layer," Scientific Reports 6, 21324 (2016).

[51] The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense.